

# MULTIFUNCTIONAL MAGNETODIELECTRIC COMPOSITES FOR ANTENNA AND HIGH FREQUENCY APPLICATIONS

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**Abstract**--Miniaturization of high frequency antennas while maintaining desirable bandwidth, impedance, and loss characteristics has recently attracted great attention in part due to the development of metamaterials. Ideal magnetodielectric materials should have the largest possible index of refraction  $n=(\mu\epsilon)^{1/2}$  with similar  $\mu$  and  $\epsilon$ , which match the impedance  $\eta=(\mu/\epsilon)^{1/2}$  of the materials to the environment and improve the antenna bandwidth. One approach to achieve such magnetodielectrics is to embed magnetic materials in a dielectric matrix. In this work, we have prepared and characterized a series of magnetodielectric composites with oriented Fe flake inclusions in an insulating dielectric polymeric matrix. The Fe flakes were prepared by mechanically deforming commercial Fe particles into sub-micrometers thick with aspect ratio (width/thickness) over 100. Several methods were employed to uniformly mix the Fe flakes in polymer matrix over a wide range of volume concentrations. Alignment is achieved either by using external magnetic field or flow method. High frequency complex permeability and permittivity values for the various loaded composites were measured and analyzed. These magnetodielectric composites indeed have high  $\mu$  and  $\epsilon$ , which can be matched by adjusting volume concentration.

**Keywords:** magnetic composites, permeability, permittivity, magnetic loss, magnetodielectric materials.

## I. INTRODUCTION

With ever increasing demands for miniaturizing high frequency device as a result of the rise in demand for portable communication, composite materials with high index of refraction while maintaining desirable

bandwidth, impedance, and loss characteristics have gained lots of interests. The natural method for miniaturizing an antenna is to increase the index of refraction,  $n=(\mu\epsilon)^{1/2}$ , where  $\mu$  and  $\epsilon$  are the permeability and permittivity of the material, respectively. Previous attempts in antenna miniaturization have focused on non-magnetic media with very high permittivity [1], but the bandwidth ( $\sim 1/\epsilon$ ) and impedance matching characteristics ( $\eta=\mu/\epsilon$ ) of such antennas tend to suffer [2].

An alternative approach involves utilizing the additional degree of freedom offered by the magnetic part of the index of refraction. The advantage of using such so-called magneto-dielectric materials with high  $\mu$  and  $\epsilon$  is rather obvious. The creation of a material with a high and balanced combination of  $\mu$  and  $\epsilon$  would provide a substrate with a sufficiently high index of refraction while optimizing the bandwidth and impedance. However, the choice of viable single-constituent materials with high  $\mu$  and  $\epsilon$  is limited, so composite material is an attractive alternative. The use of spherical inclusions is simple. However, because of the demagnetization factor, the apparent permeability  $\mu_{app}$  is generally less than 3 for spherical particles, regardless the possible high intrinsic permeability and thus limited in benefit [3]. Consequently, high permeability is hard to be achieved in magneto-dielectrics with spherical inclusions. And the increased loss due to eddy currents in such a material is also a significant problem.

Several attempts have been made to overcome these difficulties. Improvements have been realized by engineering the shape of the inclusions, such as non-magnetic Split Ring Resonators [4] and small electromagnetically embedded circuits [5], which act as artificial magneto-dielectrics, or by alternating layers of

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engineered ferrites and readily available dielectrics [6, 7]. In an effort to simplify the production of bulk quantities of antenna substrate; this work is centered on the preparation, characterization, and resultant magneto-electrodynamic properties of aligned, high axial/planar ratio ferromagnetic inclusions, embedded within an insulating polymeric matrix.

## II. EXPERIMENTAL

Flake-like inclusions were fabricated by mechanically deforming 100-150  $\mu\text{m}$  Fe-based particles [Hoeganaes Corp., TC80], using a high-energy ball milling process as detailed in our previous publication [8]. The resultant flakes exhibit a high aspect ratio, with lateral dimensions on the order of 50-100 $\mu\text{m}$  and thickness of sub-microns. Flakes of these dimensional ratios, combined with proper alignment, help to reduce the demagnetizing effect and eddy current loss, that occurs in their granular precursors. These flakes can be assumed as laminate structures whose eddy current losses are given by Eq. 1 [9], in which an increase in thickness squares the loss:

$$W_e = \frac{kB^2t^2}{\rho} f^2 \quad (1)$$

Loss is minimized by both reducing the flake's thickness as well as aligning the flakes, so that their narrow dimension is perpendicular to the magnetic fields to achieve minimum cross-section for eddy current. To further eliminate the eddy current cross flakes, some flakes are coated with thin amorphous silica layer using the base-catalyzed sol-gel technique [8] and compared with uncoated flakes.

The magnetic field of an electromagnetic wave normal to the surface of an antenna would parallel the surface of the substrate, thus alignment must be achieved in the planar dimension. So, the composite samples for this study were prepared via two different methods to achieve such alignment, which work at different loading fractions. For low concentrations, (1%-10% vol) flakes were manually mixed into a styrene-based resin and cured in a magnetic field to promote alignment. (Figure 1) But the viscosity of the mixture prevented useful loading at volume fractions higher than ten percent. For medium

concentrations (5%-45% vol), flow alignment is used by utilizing the flake's high geometrical aspect ratio. Granular polystyrene and flakes were mechanically mixed and extruded through a high-shear mixer at a

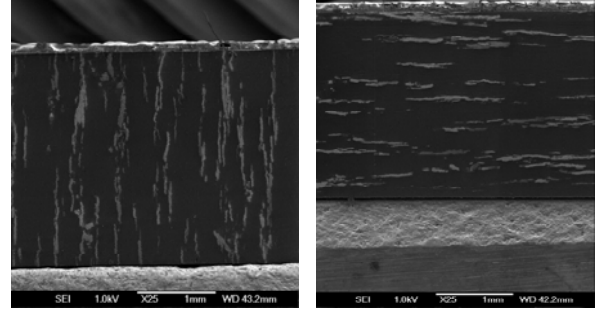


Fig. 1 SEM pictures of field aligned composites at 10%vol. The alignment can be achieved at different direction.

polymer extrusion temperature of 170°C. The extruded mix was flow aligned within a hot press. With the flow during a hot press, flakes will align their large surface parallel to the plane of the substrate. Attempts to improve alignment were made through breaking, stacking, and repressing the films. (Figure 2) Volume concentrations greater than 45% were difficult to mix and extrude due to high viscosities. Samples at high volume concentration up to 76%vol are made by mixing and compacting without promoting flakes alignment as reference samples

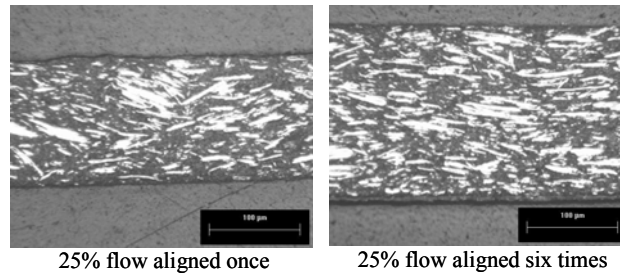


Fig.2 Flow alignment achieved at high concentration (25%vol) with different times of pressing

to complete whole concentration spectra.

X-ray diffraction (XRD) measurements were performed on the disk-shaped samples in a Philips XRD-3100 using a Bragg-Brentano geometry. According to our previous study [8], the Fe flakes generated by mechanical deformation tend to have (100) orientation along the surface. So the alignment of the inclusions can be characterized by the ratio between the intensities of the (200) and (110) peaks.

Permeability and permittivity of such flake composites were measured by an Agilent 4294A Precision Impedance Analyzer, using 16454A magnetic test and 16451 dielectric test fixtures. Samples with toroid and disc shape are used for these 2 fixtures

### III. RESULTS AND DISCUSSION

We have demonstrated permeability and permittivity spectrum with different volume concentration of flakes and different matrix materials. Permittivity data shown in Figure 3(top) shows an increase in permittivity as a function of increased volume fraction (combined with decreasing alignment quality shown in XRD data). Both the increase in volume fraction and the decrease in alignment conspire to enlarge the volume of conducting regions and thus higher loss, as expected. And it will experience a

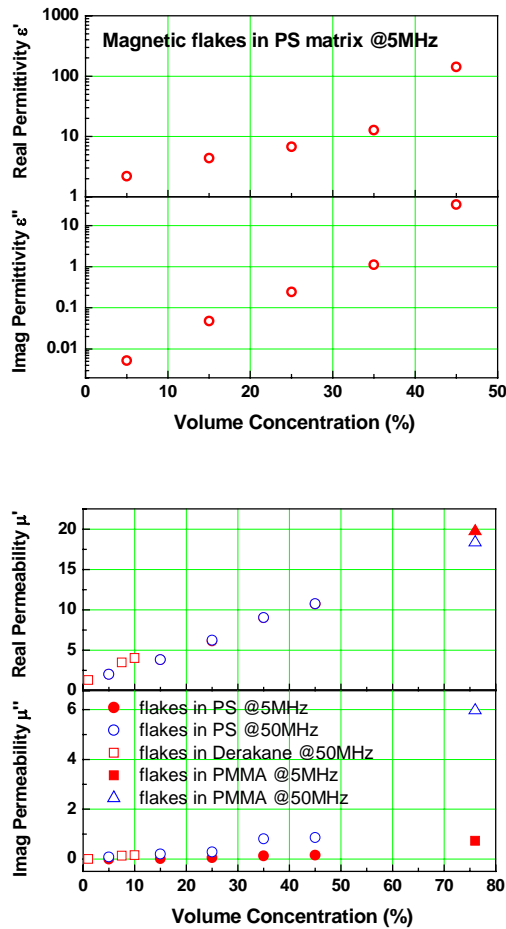


Fig.3 Volume concentration dependence of permeability and permittivity for different matrix materials.

significant increasing around percolation ratio of about 40% and become unusable at high volume concentration. The permeability is shown to be less sensitive to the alignment of the flakes and depends more on the volume fraction of the magnetic inclusions and almost independent to the matrix materials, as seen in Figure 3(bottom). At volume concentration around 25%, values of these two parameters will match to each other and makes it a good candidate for magnetodielectric materials.

In high frequency measurement, it is clearly shown that composite materials with multiple pressing (thus better alignment) have higher Q factor and more stable dielectric constant over frequency spectrum (Figure 4-top). If we describe the degree of alignment by XRD (200)/(110) peak ratio, the alignment dependence of loss in such composite materials can be clearly seen. (Figure 4-bottom)

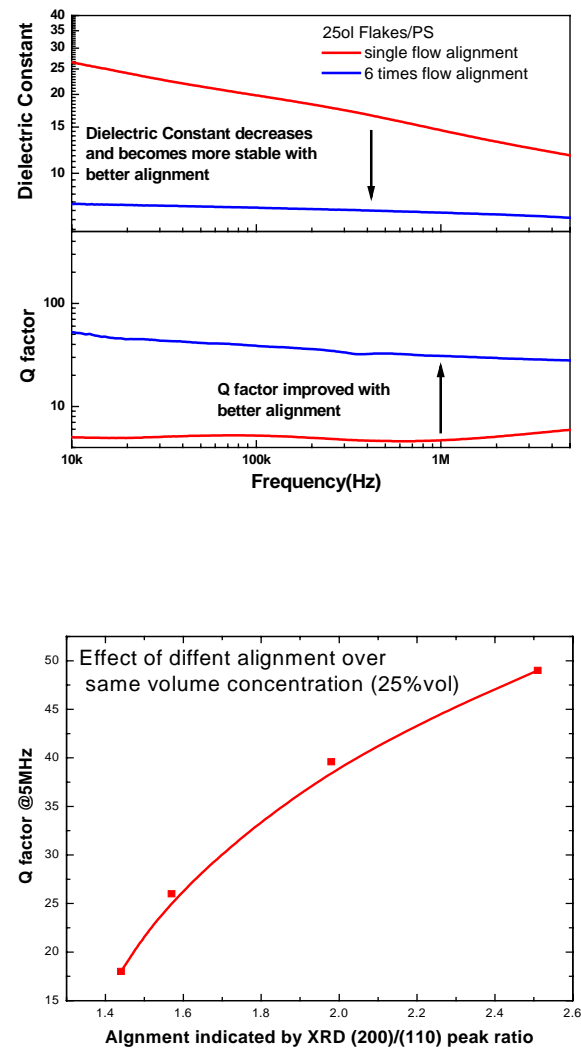


Fig.4 (top) Effect of flow alignment on permittivity and loss; (bottom) alignment dependence of Q factor

Even with these methods to achieve better alignment, it is still difficult to entirely avoid local agglomeration of flakes, which can be a significant source of loss due to the eddy current cross flakes. It is also difficult to achieve better alignment in composites with higher loading. So it is found that pre-coating of flakes before fabricating laminated composites is necessary. With silica coating provided by simple process described before, composites based on coated flakes show a much better loss property and more stable dielectric value than uncoated reference sample with same loading and extruding process (Figure 5).

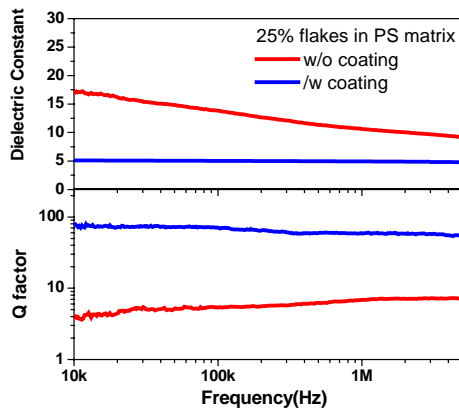


Fig.5 Effect of coating on dielectric loss.

#### IV. CONCLUSION

This study shows that magneto-dielectric composites can be tuned to desirable values of  $\mu$  and  $\epsilon$  in the range of **2 to 30** and **1 to 20**, respectively, through the use of well-aligned flake-like magnetic inclusions. These two parameters will match to each other at value around 5-10 at 20-30% volume concentration. Flake inclusions benefit the material by reducing both demagnetizing factors and eddy currents, when compared to their spherical precursors. Since alignment greatly affects the permittivity results, the alignment quality must be considered to achieve the desired values. Insulating coating on individual inclusions will further decrease the loss. Future study focuses on both improving alignment and reducing flake dimensions to further suppress eddy currents and sustain low- loss

magnetic and dielectric properties at greater frequencies. Once achieved, this form of magneto-dielectric can be synthesized as viable antenna substrates.

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